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# Thermally induced surface integrity changes of ground WC-Co hardmetals

J. Yang[1,2], J.J Roa[1,3], M. Schwind[4], M. Odén[2], M.P. Johansson-Jõesaar[2,4] , J. Esteve[5] and L. Llanes[1,3]*

*1 CIEFMA - Universitat Politècnica de Catalunya, Barcelona 08028, Spain*
*2 IFM - Linköping University, Linköping 58183, Sweden*
*3 CRnE - Universitat Politècnica de Catalunya, Barcelona 08028, Spain*
*4 SECO Tools AB, Fagersta 73782, Sweden*
*5 Universitat of Barcelona, Barcelona 08028, Spain*

* Corresponding author. Tel.: +34 934011083; fax: +34 934016706. *E-mail address*: luis.miguel.llanes@upc.edu

**Abstract**

Ground hardmetals are exposed to high temperatures during both processing (e.g. coating deposition) and use (e.g. as a cutting tool). However, studies on thermally induced changes of surface integrity are limited. Here we address this by means of FIB/FESEM and EBSD investigation, with special focus on the binder phase characterization. Our findings indicate that thermal treatment causes two main surface modifications. First, an unexpected microporosity appears in the binder within the subsurface layer when ground surfaces are heated. Second, the metallic phase underneath the ground surface experiences metallurgical changes, in terms of grain and crystallographic phase structures. The mechanisms responsible for these modifications of the binder are discussed in terms of grinding-induced and thermally-reversed phase transformation as well as recrystallization phenomena. We also note that no additional heat treatment related changes such as microcracking and carbide fragmentation in the subsurface layer, are discerned.



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*Keywords:* Grinding; Thermal effect; Surface integrity; Cemented Carbides

## 1. Introduction

WC-Co cemented carbides, often termed as hardmetals, are composite materials containing ceramic particles embedded in a metallic binder. As a result of such unique combination, they exhibit excellent mechanical and tribological properties, such as high hardness, strength, fracture toughness, and wear resistance. In modern industry, hardmetals serve as the backbone material for cutting and metal-forming tool applications [1,2].

Due to its relatively high hardness, diamond wheel grinding is commonly applied to machine hardmetal tools and components. As a consequence of such abrasive operation, it is now established that surface integrity of cemented carbides is altered, particularly in terms of surface texture, subsurface damage and residual stress state; and thus, mechanical and tribological performance are also affected [3,4].

During both processing (i.e. coating deposition) and effective operation of hardmetal tools, large amount of heat is typically generated [2,4,5]. For instance, temperatures at the cutting edge of inserts during machining may reach values ranging from 650ºC to 1200ºC [5,6]. Such high temperatures could result in material degradation and affect the tool life. Within this context, it is essential to study how the surface integrity is affected by grinding and a subsequent exposure to high temperature.

The mechanical properties of WC-Co cemented carbides, such as toughness and fatigue, are strongly dependent on the local mechanical response of the metallic binder phase (even though it is the minority phase) [7]. In grinding-related studies, however, no special attention has been considered on possible alterations taking place in the binder, as compared to those occurring in the hard/brittle carbides and the global damage such as, e.g., microcracks that develop both at the surface and subsurface levels.

In this study, the main objective has been to evaluate thermally induced effects on the surface integrity of ground hardmetals with emphasis on the microstructural and


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metallurgical changes induced within the binder. It should be noted that the relief of grinding-induced compressive residual stresses, by means of thermal annealing, is not addressed in this investigation. Related to this issue, the authors has reported on studies concerning mechanical strength, scratch resistance and contact damage response of hardmetals elsewhere [8-10].

## 2. Experimental details

The hardmetal studied in this work is a WC-13wt.% Co grade with a carbide mean grain size of about 0.7 μm. Fig. 1 schematically outlines the process steps used to obtain the different surface finish variants investigated. The grinding operation using a diamond abrasive wheel and coolant followed an industrial protocol, commonly implemented for inserts by SECO Tools AB. The resulting surface condition is referred to as G in this study. To assess thermally-induced changes of the ground hardmetal surfaces, some G specimens were heat-treated at 920 °C for 1 h in vacuum [11,12]. The ground and thermal treated condition is referred to as GTT.

Subsurface features of the two conditioned samples were examined using a dual beam Zeiss Neon 40 work station, equipped with focused ion beam (FIB) and field emission scanning electron microscopy (FESEM). A series of cross-sections orthogonal to the grinding surface were FIB-milled, and imaged by FESEM.

In order to explore more details about the deformation phenomena within the binder phase, electron back scattered diffraction (EBSD) was used to inspect the cross-sections. EBSD data acquisition was conducted using a Zeiss Supra 40 high resolution SEM, using 20 kV voltage. In doing so, the specimen was tilted 70° against the electron beam. Data was collected across an area 30 × 20 μm$^2$ in size with a step size ranging between 31 - 35 nm. Crystallographic phase maps were then constructed by employing the Channel 5 software.

## 3. Results and discussions

Grinding is a severe abrasive process, involving thousands of diamond grains with sharp edges cutting the workpiece surface. Meanwhile, the ascribed thermal effect is inhibited by the cooling lubricant. The corresponding subsurface damage scenario may be assessed by direct examination of FIB-milled transverse-sections, perpendicular to the grinding direction (Fig. 2). A well-defined thin (in-depth) surface layer, highlighted by dashed white lines, is clearly distinguished for the G sur-

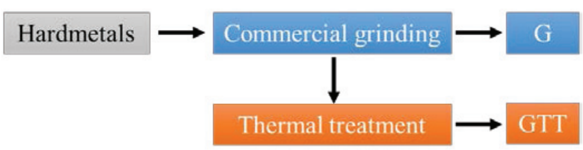


Fig. 1. Scheme of material removal and thermal annealing processes followed for attaining the surface finish variants studied.

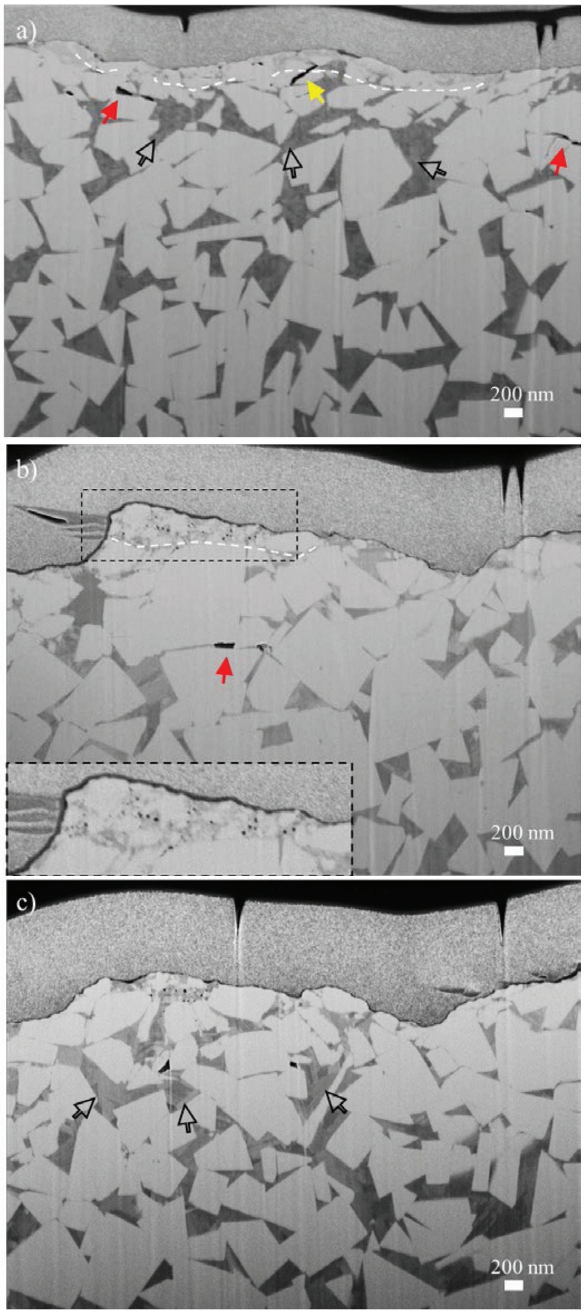


Fig. 2. FIB cross-sections showing subsurface damage: (a) G; and (b), (c) GTT. Cracks following either WC/Co interface or transgranular paths are indicated by red and yellow arrows in (a) and (b), respectively. Subsurface layer containing fragmented WC grains and smeared Co phase is identified, from the underneath bulk material, by dashed white lines. Dashed rectangle at the left bottom corner in (b) is the enlarged view of the dashed rectangle at the left top. Black outlined arrows in (a) and (c) point out the representative Co region to highlight its morphology features, respectively.

face condition (Fig. 2a). It includes fragmented carbides, microcracks and smeared binder. Crack paths are identified to be either WC/Co interfaces (red arrows) or through WC-grains (yellow arrows).

Thickness of the referred layer as well as cracking scenario are not affected by the subsequent heat treatment (Fig. 2b). This is somehow expected since heat treatment does not imply any mechanical action. However, one distinct change discerned in the GTT condition is the presence of microvoids within the subsurface layer, as indicated by the dashed rectangle in Fig. 2b. A closer examination reveals that those microvoids are localized in the binder phase. Besides the apparent subsurface features described above, another significant difference between G and GTT specimens relates to the morphology of the binder phase underneath the surface layer. Aiming to clarify this issue, another cross-section image of GTT Fig. 2c, containing a relatively larger area fraction of the metallic binder than the one presented in Fig. 2b, was chosen to highlight deformation features within this phase. The Co phase exhibits severe plastic deformation in the ground sample, especially at the near surface region. It is evidenced by pronounced image contrast at length scales smaller than the binder thickness between the carbide grains (e.g. binder regions pointed out by black outlined arrows in Fig. 2a). Main reasons for the referred image contrast may be either formation of subgrains or existence of regions with high density of deformation features, including slip and twinning traces, as well as induced phase transformation from the metastable fcc structure to the stable hcp one. Nevertheless, detailed information for supporting such hypothesis requires additional transmission electron microscopy analysis which is out of the scope of this study. In general, this is observed within a subsurface region deeper than the one where cracks are detected. The WC phase is also expected to deform accordingly, in agreement with the residual stress profile (down to depths as large as 12 μm) reported for this surface state [8]. This deformation morphology of the binder phase vanishes after thermal annealing. Instead the Co-phase display a larger lath-like structure, indicating metallurgical alterations in terms of phase transformation and recrystallization [13-15]. Moreover, these changes are also postulated to be responsible (at least partly) for relief of the grinding-induced residual stresses.

Phase transformation resulting from thermal annealing is directly supported from EBSD phase mapping of the Co phase for G and GTT specimen (Fig. 3). In the band contrast map of EBSD patterns, WC grains are presented in greyscale, whereas the red and blue color scales are applied to show the pixels indexed as fcc and hcp Co phases, respectively. It is found that grinding-induced phase transformation, from original fcc into hcp phase is concentrated in a 5 μm thick subsurface region (Fig. 3a). The situation is reversed in the GTT specimen (Fig.3b). Within this context, it should be highlighted that such phase transformation is accompanied by a slight (anisotropic) volume change from one crystal structure to another. Based on these observations we propose that this phase transformation together with the expected recrystallization (at 920 ºC for a heavily cold-worked material with melting temperature around

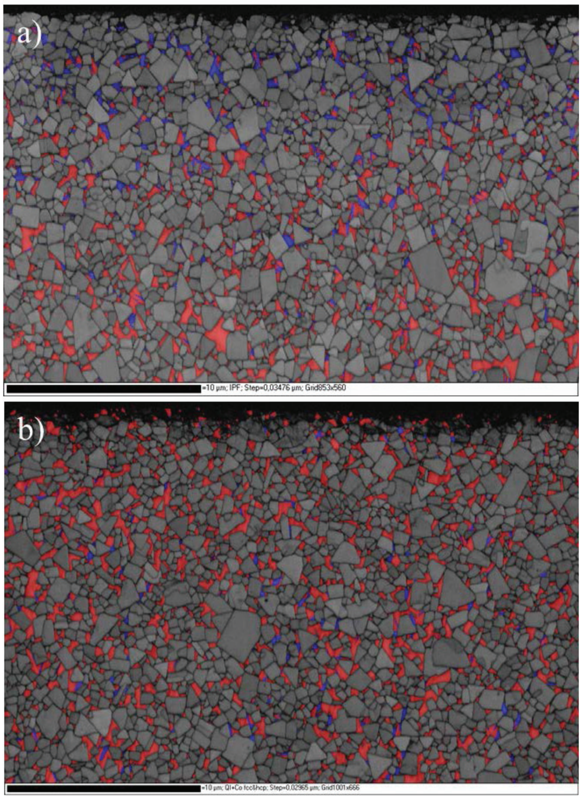


Fig. 3. EBSD phase map overlapped to the band contrast map for the metallic Co binder with red and blue colors denoting the fcc and hcp Co phase, respectively, for samples with two different surface finish: (a) G and (b) GTT. Scale marker = 10 μm.

1330 ºC), as the main reasons for the microvoid formations within the binder phase. This is supported by recalling that microvoids are only found in the severely deformed surface layer of GTT specimens and the close similarity between the size of the microvoids and grain substructure within the binder. From a performance viewpoint, such microvoids may be detrimental especially under service conditions involving high temperature and tribomechanical exposure, as then creep-like phenomena could also become operative. Similar systematic study has not yet been conducted in cutting tools after being subjected to working conditions, although research in this direction is currently under progress. However, above ideas are somehow validated by the findings of Denkena and Breidenstein [16,17] on cohesive damage, i.e. flaking of the coating with adhering substrate material of PVD-coated hardmetal. This failure mode is different from the adhesive one, i.e. simple flaking off of the coating material. In this regard, the explanation of cohesive failure of ground and coated tools, observed by them during cutting tests, should not only consider residual stress distribution issues, but rather the combined effect of all the thermal-induced surface integrity changes here reported.

## 4. Summary

The influence of thermal treatment on the surface integrity of ground WC-Co hardmetals has been investigated. In doing so, advanced characterization techniques such as FESEM, FIB and EBSD have been employed. It is found that thermally induced effects are localized in the binder phase and within a thin subsurface layer. They are described in terms of emergence of an unexpected microporosity together with metallurgical alterations: development of a recrystallized subgrain structure and reversal of a grinding-induced phase transformation. We suggest that these phenomena are related to each other. On the other hand, grinding-induced damage such as microcracking and carbide fragmentation is not affected by exposing the hardmetal to high temperature.

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